MODEL TO ASSESS ENERGY CONSUMPTION IN INDUSTRIAL LUMBER KILNS

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ABSTRACT

In this work, a kiln energy model was developed with the main objective of assessing energy consumption in industrial lumber kilns. The model simulates kiln energy consumption on the basis of a simplified description of kiln technologies, energy systems and lumber characteristics, and it requires a minimum set of empirical parameters that are calibrated in practice. In this study, the model calibration was performed for a laboratory scale conventional kiln and three experimental drying runs of 50 mm thick spruce-pine lumber. The results of this study illustrate how the kiln energy model is calibrated, compares experimental and simulated MC, energy and water consumption, and describes how the model simulates different components of energy consumption that can be used to evaluate potential energy saving strategies.

Keywords: Conventional kiln, lumber drying, mathematical model, energy efficiency, heat losses.

INTRODUCTION

A conventional kiln is relatively simple to operate and maintain, and it is a cost-effective technology for wood drying. The downside of this technology is energy efficiency. A conventional kiln consumes around 50% more energy than that required to evaporate the water. Energy consumption in a conventional kiln is required for moisture evaporation, heating the kiln and lumber, kiln ventilation, thermal losses, air leakage, and air humidification. Kiln maintenance could reduce air leakage and reduce the humidification requirements, but the benefits in terms of energy savings are usually small. Higher reduction in energy consumption can be achieved by dehumidifier units, vent heat exchangers, and air drying, but these strategies usually require considerably modifications to an existing commercial process. To assess the economic viability of potential energy saving strategies, a computer model was developed and tested to estimate energy consumption in industrial kilns.

Kiln energy consumption has been measured and simulated by several authors (Breiner *et al.* 1984, Davis 1954, Esping 1982, Elustondo and Oliveira 2006, Elustondo and Oliveira 2007, Fortin *et al.* 2004, Hopper and Toennisson 1980, Kininmonth *et al.* 1980, Kudra 2004, Laytner and Arganbright 1984, Menshutina *et al.* 2004, Mujumdar 1995, Simpson and Tschernitz 1980, Simpson 1991, Taylor 1979, Taylor 1982, Salin 2004, Shottafer and Shuler 1974), and there numerous well known measures that can be taken to reduce kiln energy consumption (such as the use of direct-fired energy systems, installation of heat exchangers in kiln vents, partial air drying of green lumber, lumber preheating with kiln exhaust air, optimization of drying schedules, reduction of air flow velocity, lumber sorting before drying, and season planning). Depending on the case, only one or two of these strategies may be practical for a particular drying operation. Therefore, the model developed in this study is a practical tool to assess industrial drying operations and determine the energy saving strategy that generates the best return of the implementation cost.

KILN ENERGY MODEL

Conventional temperature kilns use hot air at controlled velocity, temperature and relative humidity to evaporate moisture from the lumber. Figure 1 depicts the basic components of conventional kiln drying. Inside the kiln, lumber is arranged in layers that are separated by narrow strips (usually 20 mm) to allow the flow of air between layers. As the air flows between the lumber layers, the dry-bulb temperature reduces (unless the wood is hotter than the air), and the wet-bulb temperature remains the same (unless there is condensation over the lumber surfaces). Energy for drying is supplied by an energy system, and the moisture evaporated from the lumber is released outside the kiln through a ventilation system. Conventional kilns commonly also include a humidification system to compensate for humidity losses due to uncontrolled air leakage.
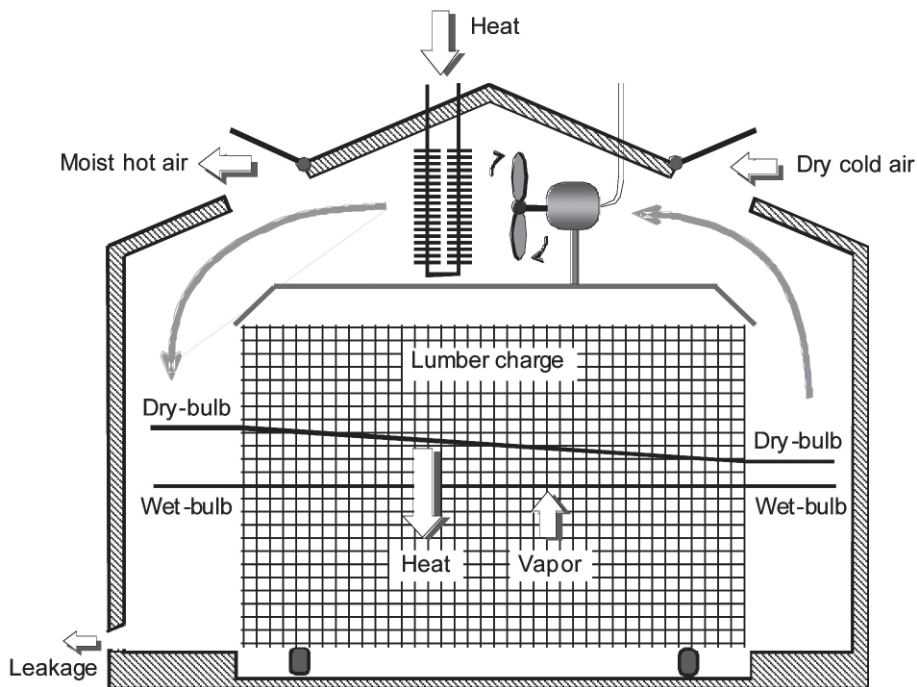

Figure 1: Basic components of kiln lumber drying

Figure 2 shows a diagram of a kiln during humidification (using low pressure steam). The figure refers to the case of lumber warm-up, in which a certain amount of condensation occurs in order to avoid premature uncontrolled drying. As it is shown in the diagram, condensation corresponds to the situation in which dry-bulb temperature corresponds to the wet-bulb temperature.
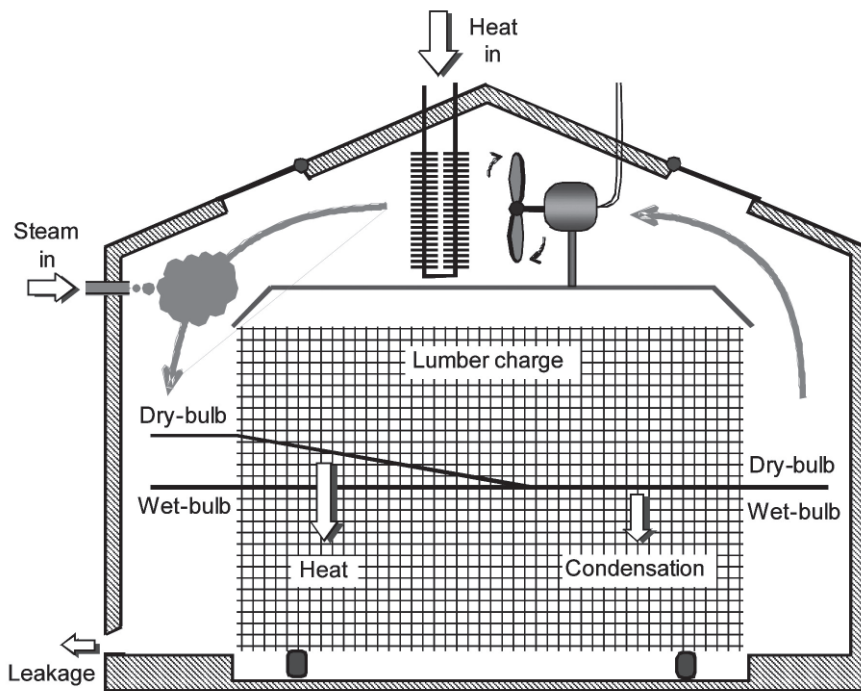
Figure 2: Lumber warm-up with humidification system

Figure 3 illustrates a section of a conventional kiln showing all the heat and mass flows simulated in the kiln energy model. These heat and mass flows are the following:

• *Heat for drying:* Includes the heat required to transform water into vapor and the heat required to break molecular bonds between wood fiber and absorbed water

• *Heat for warm-up:* Is required to increase the kiln and lumber temperature from its initial values to the dry-bulb set-point temperature

• *Thermal conduction:* Thermal losses through the kiln insulation are proportional to the temperature difference between the inside and the outside of the kiln

• *Kiln ventilation:* Is used to replace the kiln moist air with fresh air from outside. Kiln ventilation consumes heat to warm-up the fresh air that flows into the kiln

• *Low pressure steam:* Low pressure steam for humidification (<1 kpa) is normally warmer than the kiln air, thus it does not consume heat for warm-up. Nevertheless, heat is supplied by an external boiler with typical energy efficiencies of around 80%

• *Cold water spray:* Cold water spray for humidification is evaporated in the kiln, thus it consumes heat that is supplied by the kiln heating system

• *Air leakage:* Air leakage is a form of uncontrolled venting. Heat losses associated with air leakage are usually small, but uncontrolled leakage can considerably increase the humidification requirements

• *Direct-fired heat:* In this type of kiln energy systems, the hot gases of combustion are released directly inside the kiln

• *Indirect-fired heat:* In this type of kiln energy systems, the hot gases of combustion are used to heat-up a thermal-fluid (thermo-oil, steam, hot-water), and then the hot thermal-fluid is pumped through heat exchangers that are located inside the kiln

• *Electricity:* Electric power is required for the kiln fans and the burner blower (in the case of direct-fired kilns). Additionally, 10% to 20% of the electric power is lost inside the fan motors
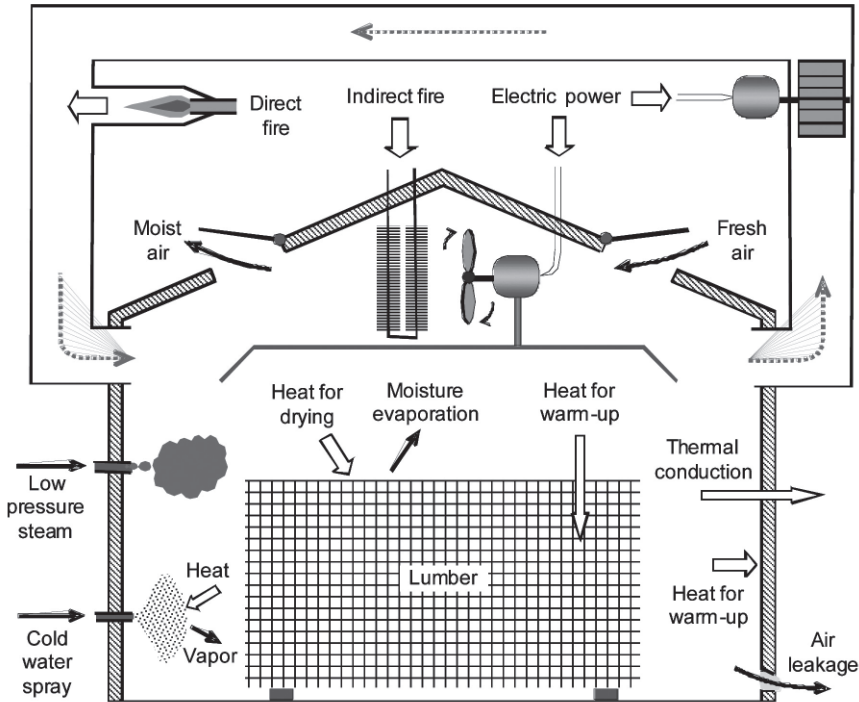
Figure 3: General diagram showing all components of the kiln energy model

The kiln energy model combines two types of energy systems and two types of humidification systems within a single unit operation. This provides the capability to simulate most of the conventional kilns that are typically found in industry. The mathematical solution is obtained by solving the simultaneous the heat and mass balances with well know thermodynamics equations. The detailed implementation of these equations is rather complicated because of the large number of components involved, thus the details concerning the mathematical implementation are not included in this paper. This paper only describes the simplified equations that were used to solve the heat and mass balances in a way that is suitable for kiln energy assessment by commercial operators.

Airflow heat balance

The mass flow (m) and enthalpy (h) balances concerning the heat transferred from the air to the lumber (Q) are calculated between the inlet and the outlet sides of the lumber load. For simplicity, it is assumed that the airflow between the lumber layers only contains pure air (a), vapor due to the air humidity (v), and vapor produced by moisture evaporation (vap):

$$0 = m_{vap} + m_v^{in} - m_v^{out} \tag{1}$$

$$Q = m_{vap}\, h_{vap} + \left(m_a\, h_a^{in} + m_v^{in}\, h_v^{in} \right) - \left(m_a\, h_a^{out} + m_v^{out}\, h_v^{out} \right) \tag{2}$$

Heat transferred from the airflow to the lumber is divided into the sensible heat absorbed by the lumber (QL) and the enthalpy (h) difference between the produced vapor (vap) and the moisture (mc) evaporated from the lumber:

$$Q = Q_L + m_{vap}\left(h_{vap} - h_{mc}\right)$$

(3)

Then, by combining these three equations, the heat balance is re-written on the basis of the average properties between entry and exit sides of the lumber load:

$$Q_L = m_a\left(h_a^{in} - h_a^{out}\right) + m_v\left(h_v^{in} - h_v^{out}\right) - m_{vap}\,\Delta h_{vap}$$

(4)

Where:

$$\Delta h_{vap} = \tfrac{1}{2}\left(h_v^{in} + h_v^{out}\right) - h_{mc}$$ = Average heat of evaporation

$$m_v = \tfrac{1}{2}\left(m_v^{in} + m_v^{out}\right)$$ = Average vapor flow between the lumber layers

For simplification, enthalpy differences are calculated on the basis of heat capacities (Cp) and temperature drop across the load (ΔT_{DB}). Mass flow are calculated on the basis of density (ρ), air velocity (v) and total area (A) available for the airflow. The relative volume of air and vapor in the airflow are calculated on the basis of total pressure (P) and vapor partial pressure (P^v). Finally, lumber (L) sensible heat is calculated on the basis of density, heat capacity, and the time (t) derivative of the average lumber temperature (T):

$$\rho_L\,Cp_L\,\frac{dT_L}{dt} = v\,A\left(\rho_a\,Cp_a\,\frac{P - P^v}{P} + \rho_v\,Cp_v\,\frac{P^v}{P}\right)\Delta T_{DB} - m_{vap}\,\Delta h_{vap}$$

(5)

Drying rate (m_{vap}), lumber temperature (T_L) and temperature drop across the load (ΔT_{DB}) are unknown variables of the process, and they need to be simulated by the model. For the purpose of industrial kiln assessment, these three parameters are estimated on the basis of the following simplified models:

Drying rate

An accurate drying rate simulation requires a comprehensive description of the drying process (lumber dimensions, dry-bulb temperature, wet-bulb temperature, and air velocity) and wood physical properties (heat capacity, basic density, thermal conductivity, gas permeability, diffusion coefficient, and capillarity). In this model however, a simplified approach was proposed to estimate drying rate with an empirical equation that is calibrated with experimental kiln data. The required experimental data is the total drying time, and lumber initial and final moisture content.

In the simplified approach, it is assumed that lumber drying is controlled by moisture diffusion. This means that lumber drying rate is calculated as a diffusion coefficient (D_{eff}) multiplied by the difference between actual moisture content (MC) and equilibrium moisture content (EMC). Theoretically, the diffusion control model is only valid for MC below fiber saturation point (FSP), but it was found in

practice that after calibration, the diffusion control model can be applied to the entire drying process. For this application, the diffusion control model is calibrated using the following empirical MC*, EMC* and FSP* parameters:

   • EMC* = The apparent EMC that results from assuming that the experimental drying rate under diffusion control reduces approximately linearly with the reduction of MC
   • FSP* = The apparent FSP that correspond to the MC at which the experimental drying rate starts reducing approximately linearly with the reduction of MC
   • MC* = The effective MC that is equal to the actual lumber MC for drying below FSP*, and equal to FSP* for drying above FSP*

By using these parameters, the simplified drying rate model results in the following equation:

$$\frac{dMC}{dt} = -D_{eff}\left(MC^* - EMC^*\right) \quad ; \quad \begin{cases} MC^* = MC & \text{for } MC < FSP^* \\ MC^* = FSP^* & \text{for } MC > FSP^* \end{cases} \tag{6}$$

The relationship between D_{eff} and temperature is obtained from literature (Siau 1995). Literature indicates that D_{eff} is equal to a constant (D_0) multiplied by an exponential function of the energy of activation ($\Delta H=34150$ kJ/kmol), the ideal gas constant (R=8.314 kJ/kmol.K), and the absolute (Kelvin) temperature (T):

$$D_{eff} = D_0\, e^{\left(-\Delta H/R\,T\right)} \tag{7}$$

It was found experimentally that for 50 mm spruce-pine lumber, EMC* and FSP* were around 12% and 45% respectively. As an example, Figure 4 shows the comparison between experimental and model drying rate for $D_0 = 8302$ 1/hr. For industrial kiln assessment, the simplified drying rate model requires calibration. Calibration consist in finding the D_0 value for which the integral of equation 6 satisfy the initial MC, final MC and total drying time measured experimentally.
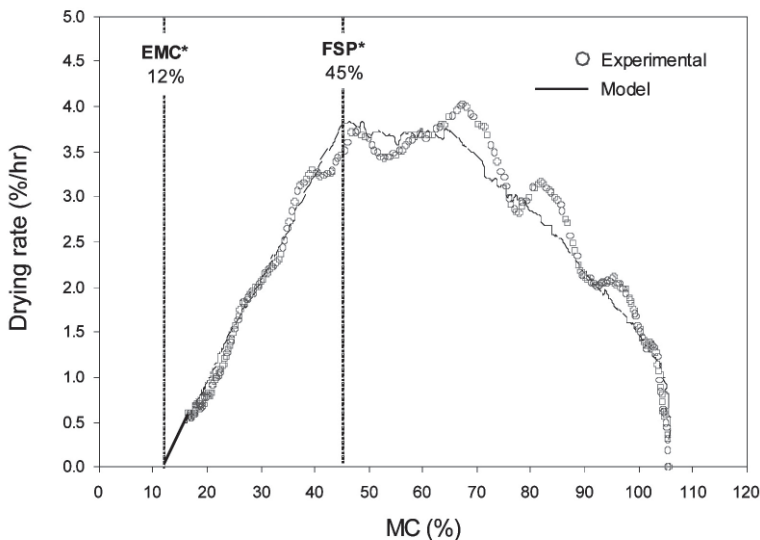

Figure 4: Experimental and model drying rates for drying 50 mm spruce-pine lumber

Lumber temperature

To estimate lumber temperature it is assumed that moisture evaporation occurs only at the lumber surfaces. During warm-up, lumber surface temperature is assumed to be equal to the wet-bulb. During drying, lumber surface temperature is assumed to be equal to the dry-bulb. Then, heat flow into the lumber is calculated as one-dimensional thermal conduction in the direction (l) of the lumber thickness. The lumber thermal conductivity (k_L) is obtained from literature (Siau 1995), and the model also considers the possibility of ice concentration (c_{ice}) inside the lumber:

$$\rho_L \, Cp_L \, \frac{\partial T_L}{\partial t} = \frac{\partial}{\partial l}\left(k_L \, \frac{\partial T_L}{\partial l} \right) - \Delta h_{ice} \, \frac{\partial c_{ice}}{\partial t} \tag{8}$$

Where the ice heat of melting (Δh_{ice}) is approximately 334.4 kJ/kg (Siau 1995). In theory, free-water freezes below 0°C, but because of the various soluble substances inside the wood, wood freezing occurs gradually between 0°C and -15°C (Skaar 1972, Sparks *et al.* 2000). Therefore, the model assumes that the percentage of frozen free-water inside the wood increases proportionally to the reduction of temperature between 0°C and -15°C.

Vapor condensation

During warm-up, the temperature drop across the load (ΔT_{DB}) calculated with equation 5 may be larger than the difference between dry-bulb and wet-bulb temperatures at the entry side of the load. This means that vapor condenses over the lumber surfaces, and dry-bulb and wet-bulb (T_{WB}) temperatures are equal at the exit side of the load. Under this conditions, the drying rate (m_{vap}) model described in equation 6 is replaced by a vapor condensation model based on the partial vapor pressure (P^v) derivative and the wet-bulb drop across the load (ΔT_{WB}):

$$m_{vap} = -\, v\, A\, \rho_v \left(\frac{1}{P} \frac{dP^v}{dT_{WB}} \right) \Delta T_{WB} \tag{9}$$

During condensation, wet-bulb temperature is equal to the dew-point, thus the partial vapor pressure derivative can be estimated with the thermodynamic relationship known as Clapeyron equation (Incropera and Witt, 1996):

$$\frac{dT_{WB}}{dP^v} = \frac{R}{M_w \, \Delta h_{vap}} \frac{(T_{WB})^2}{P^v} \tag{10}$$

Where the water molecular weight is M_w=18.015 kg/kmol. Then, by taking into account that dry-bulb and wet-bulb temperatures are equal at the exit side of the load, the temperature drop across the load is determined by simple arithmetic:

$$\Delta T_{DB} = \left(T_{DB}^{in} - T_{WB}^{in} \right) + \Delta T_{WB} \tag{11}$$

Kiln Parameters

There are three heat and mass flows in the model affected by the kiln structure, namely, thermal conduction through the kiln walls, heat for warming-up the kiln, and air leakage through defective kiln sealing. For the purposes of this model, these flows are calculated using three calibration parameters, namely, the kiln heat transfer coefficient (H_K), the kiln heat capacity (Cp_K) and the total air leakage (AL_K). These calibration parameters are overall properties accounting for the entire kiln structure, and

they are determined experimentally for each particular kiln.

Thermal conduction through the kiln insulation ($Q_{thermal}$) is calculated on the basis of the kiln heat transfer coefficient (H_K) and the difference between the dry-bulb temperature and the temperature outside the kiln (T_0):

$$Q_{thermal} = A_K H_K \left(T_{DB} - T_O\right)$$

(12)

Where AK is the kiln total area including walls, roof, floor, metallic frame and concrete basis. Heat to warm-up the kiln structure (Q_{Cp}) is calculated on the basis of the kiln heat capacity (Cp_K) and the time (t) derivative of the dry-bulb. Since most of the kiln mass is concentrated in the walls, roof and floor, the kiln heat capacity is also referred to the kiln total area:

$$Q_{Cp} = A_K CP_K \frac{dT_{DB}}{dt}$$

(13)

Air leakage (AL_K) accounts for all the fresh air that flows into the kiln through openings other than the kiln vents. Contrary to common perception, air leakage in this model is not the warm moist air flowing out of the kiln (that can be easily seen in practice because it becomes foggy when the weather is cold), but the fresh air flowing into the kiln which then requires heating. Warm air flowing out of the kiln contains air leakage, moisture evaporated from the lumber, steam supplied by the humidification system, and products of gas combustion in the case of direct-fire kilns.

MATERIALS AND METHODS

The model was implemented in Microsoft-Excel and validated with three experimental drying runs of 50 mm spruce-pine lumber. Each drying run comprised 136 pieces arranged in a single pack of 17 boards across and 8 layers high (an approximately 2.8 m³ pack). Drying runs were performed in a 3.1 m long pilot scale electrically heated kiln with capacity for approximately 11 m³ of lumber (assuming 50 mm nominal lumber thickness and 20 mm stickers). The experimental pilot scale kiln was equipped with electric heaters and a cold water spray, and the kiln wall is comprised of commercial 4" aluminum fiberglass insulated panels. For each experiment, the following experimental data was collected:

• Air velocity at ambient temperature with a hot-wire anemometer
• Two 25 mm samples from each green board to determine initial MC by the oven-dry method
• Total energy consumption was recorded from a electric power use meter
• Total water consumption (cold water spray) measured with a water flow meter
• Total lumber weight before, during and after drying measured with in-kiln load cells
• Dry-bulb and wet-bulb temperatures measured and recorded with in-kiln temperature sensors
• MC during drying was calculated by the kiln controller on the basis of lumber weight and initial MC

Each drying run had markedly different initial MC so they were dried using different schedules. The set-point temperature values for the three experimental drying runs are reported in Table 1. The kiln controller was designed to record all control actions in a computer file. After the experiments, the kiln controller information was used to calculate fan power, heaters power and water volume rate at any time during the drying process.

TABLES AND FIGURES

Table 1: Schedule set-points for the three experimental drying runs

Run	Ramp[1]	Step[2]	Dry-bulb	Wet-bulb
	time	time		
	(h)	(h)	(°C)	(°C)
1	4	0	70	70
	2	10	90	70
	2	to end	90	60
2	4	0	50	50
	2	10	70	50
	2	to end	80	50
3	4	0	50	50
	2	10	60	50
	2	10	65	50
	2	10	70	50
	2	to end	80	50

[1] Temperature increases linearly to the set-point

[2] Temperature remains equal to the set-point

RESULTS AND DISCUSSION

The measured initial MC, final MC, drying time, energy consumption, and water consumption for the three experimental drying runs are reported in Table 2. As it was indicated before, the kiln energy model was not designed to simulate kiln lumber drying, but to assess kiln energy consumption on the basis of parameters that can be easily determined in practice. In this study, the main model parameters are air leakage (AL_K), insulation coefficient (H_K) and kiln heat capacity (Cp_K). Another model parameter is the lumber diffusion coefficient (D_{eff}), that is calibrated in practice by knowing initial MC, final MC and total drying time. These model parameters are real physical properties that can be estimated in practice by using indirect methods (Elustondo & Oliveira, 2007). In this particular study, model calibration was performed by finding the AL_K, H_K and Cp_K that minimize the differences between simulated and measured energy consumption, heat for warm-up and humidification requirements.

Table 2: Summary of results for the three experimental drying runs

Run	Green MC (%)	Final MC (%)	Drying time (h)	Energy consumption (MJ)	Water consumption (kg)
1	27.0	14.9	21.6	3086	631
2	38.0	14.7	36.8	2671	210
3	62.0	15.0	67.1	3894	109

The results of the model calibration for the three experimental runs are reported in table 3, and the comparison between simulated and experimental lumber MC and total energy consumption during drying are shown in Figure 5 and Figure 6. As it can be observed, D_{eff}, AL_K and H_K are lower in run 3, and this is consistent with the fact that air heat & mass transfer coefficients and internal kiln over-pressure (leakage) reduce with the reduction of air velocity. Cp_K obtained by calibration shows considerable experimental error, but the numbers are consistent with the fact that Cp_K is independent of air velocity. For corroboration, AL_K, H_K, and Cp_K were also estimated with other indirect methods.

Table 3: Experimental airflow velocity and results of model calibration

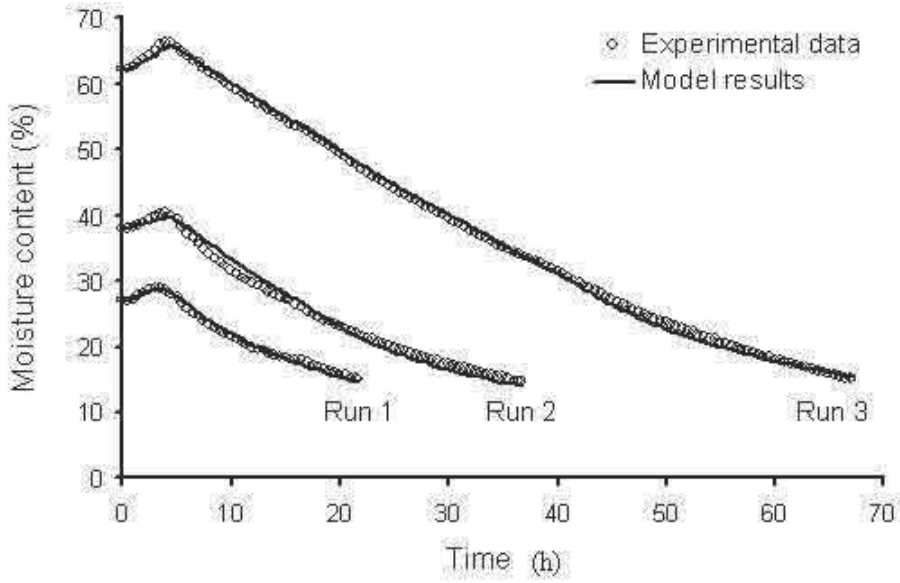| Run	Airflow velocity (m/s)	Diffusion coefficient (1/h)	Air leakage (kg/h)	Insulation coefficient (kJ/h.C)	Heat capacity (kJ/C)
1	4.4	6400	199	614	2285
2	4.4	6755	199	623	3284
3	2.3	4952	111	525	2020

Figure 5: Comparison between simulated and experimental moisture content curves
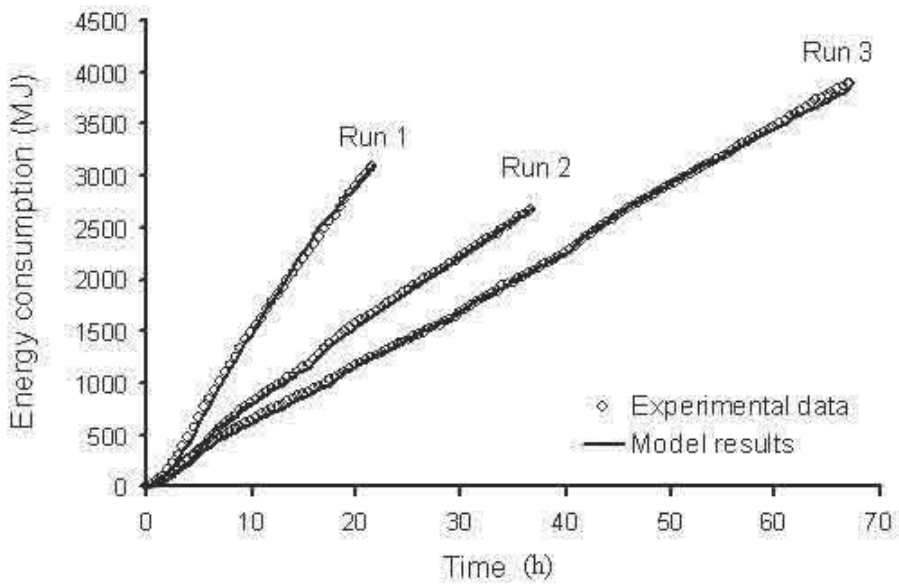

Figure 6: Comparison between simulated and experimental energy consumption curves

H_K was estimated on the basis of the kiln geometry and average thermal conductivities measured

at FPInnovations (1.12 W/m^2.C for the aluminum fiberglass panels, and 2.01 W/m^2.C for the concrete floor). Cp_K and AL_K were determined through basic heat and mass balances performed for the empty kiln. First, the kiln was warmed-up at constant heat power until the dry-bulb temperature reached the equilibrium point (around 90°C). At equilibrium, the heat power supplied to the kiln is equal to the heat losses, thus a generic heat transfer coefficient (including both thermal insulation and air leakage) was calculated with a definition similar to equation 11. Then, warm-up heat is equal to the total energy supplied to the kiln minus the integral of the heat losses. After that, the humidification system (cold water spray) was turned on until both dry-bulb and wet-bulb temperatures reached equilibrium again. At equilibrium, total water supplied to the kiln was equal to the vapor lost due to air leakage, and AL_K was calculated with a mass balance.

The parameters estimated through indirect methods were $AL_K \approx 50\text{~}150$ kg/h, $H_K \approx 450$ kJ/h.C, and $Cp_K \approx 2000$ kJ/C. Because the lumber changes the airflow distribution inside the kiln, the air leakage and heat transfer coefficient measured for the empty kiln are not technically equal to the parameters calibrated for the kiln with lumber. Nevertheless, the measured and the calibrated parameters are in the same order of magnitude, thus confirming that the model parameters are equivalent to real physical properties of the kiln.

After calibration, the kiln energy model was used to calculate the different component of energy consumption associated to each of the drying runs. Figure 7 shows the simulated components of energy consumption. As it can be observed, each drying run present a different opportunities for energy reduction depending on the following trends:

• Energy consumed for moisture evaporation increases from run 1 to run 3 due to the increase in green moisture content
• Energy losses through kiln insulation increases from run 1 to run 3 due to the increase in drying time
• Energy required for water humidification decreases from run 1 to run 3 due to the decrease in wet-bulb temperature
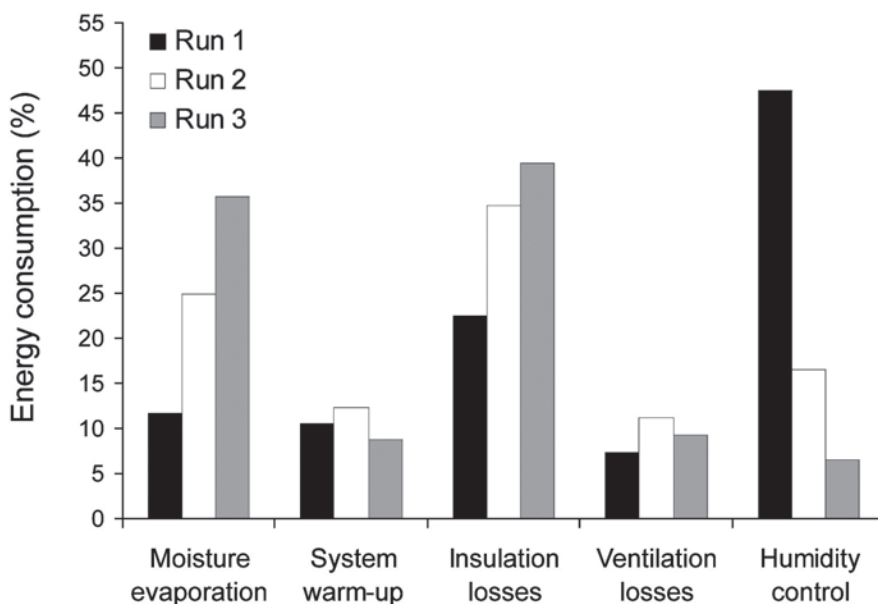

Figure 7: Simulated components of energy consumption for the three drying runs

It must be pointed out that the laboratory kiln used in this study had a relatively high air leakage

in comparison with the volume of dried lumber. Since air leakage increases air humidity losses, Run 1 (using high wet-bulb temperature) consumed considerably more energy for humidification than Runs 2 and 3.

CONCLUSIONS

A kiln energy model was developed with the main objective of assessing energy consumption in industrial lumber kilns. The model estimates kiln energy consumption on the basis of a simplified description of kiln technologies, energy systems and lumber characteristics, and it requires a minimum set of empirical parameters that are calibrated in practice. These kiln parameters are air leakage, insulation coefficient and kiln heat capacity. Additionally, the model includes a parameter to estimate lumber drying rate, that is calibrated with experimental data of drying time and lumber initial and final MC.

The model is designed to perform kiln energy assessments and subsequent analysis of potential energy saving strategies. In this study, the kiln assessment consisted in measuring initial MC, final MC, drying time, and total energy and water consumption for a laboratory scale conventional kiln. After measuring these data, the model was calibrated by adjusting the parameters until the simulated drying time, final MC and total energy and water consumption were equal to the experimental values. In an industrial kiln assessment, the determination of the kiln parameters could be different depending on the equipment and information that is available at the site.

The parameters obtained from model calibration were validated by comparing with the air leakage, insulation coefficient and kiln heat capacity measured through other indirect methods. This confirmed that the model parameters are equivalent to real physical properties of the kiln. After calibration, the model was used to simulate lumber MC, total energy and water consumption, kiln energy efficiency, and energy losses due to thermal conduction, ventilation, humidification and warm-up. In an industrial kiln assessment, simulated kiln energy efficiency and energy losses will be use determine the need of kiln maintenance and the economic viability of implementing potential energy saving strategies.

REFERENCES

Breiner, T.A.; Arganbright, D.G.; Huber, D. 1984. On-line Monitoring of Heat and Energy Consumption. In Proceedings of the North American Wood Drying Symposium, Mississippi, USA.

Davis, V.C. 1954. Steam Consumption in the Kiln Drying of Western Softwoods. *Forest Products Journal* 4(5): 258-260.

Elustondo, D.M.; Oliveira, L. 2006. Opportunities to Reduce Energy Consumption in Softwood Lumber Drying. *Drying Technology* 24: 653-662.

Elustondo, D.M; and Oliveira, L. 2007. Strategies to Reduce Energy Consumption in Kiln Drying. In Proceedings of the 10th International IUFRO Conference, Maine, USA.

Esping, B. 1982. Energy Saving in Timber Drying. Wood Technology Report No. 12. Svenska Träforskningsinstitutet, Stockholm.

Fortin, Y.; Defo, M.; Nabhani, M.; Tremblay, C.; Gendron, G. 2004. A simulation tool for the optimization of lumber drying schedules. *Drying Technology* 22(5): 963-983.

Hopper, D.L.; Toennisson, R.L. 1980. Reducing energy consumption and related costs at the saw-

mill and dry kiln. In Proceedings of Sawmill Maintenance Workshop, Nashville, Tennessee.

Incropera, F.P.; Witt, D.P. 1996. Fundamentals of heat and mass transfer. John Wiley & Sons, New York, 4th edition.

Kininmonth, J.A.; Miller, W.; Riley, S. 1980. Energy Consumption in Lumber Drying. In Proceedings of the IUFRO Conference, Division V, Oxford, England.

Kudra, T. 2004. Energy aspects in drying. *Drying Technology* 22 (5), 917-932.

Laytner, F.Y.; Arganbright, D.G. 1984. Within Kiln Variability in Transmission Heat Losses. *Forest Products Journal* 34(2): 62-68.

Menshutina, N.V.; Gordienko, M.G.; Voynovskiy, A.A.; Kudra, T. 2004. Dynamic Analysis of Drying Energy Consumption. *Drying Technology* 22 (10): 2281-2290.

Mujumdar, A.S. 1995. Handbook of Industrial Drying. Marcel Dekker, Inc., New York, 2nd edition.

Salin, J.G. 2004. Determination of the most economical drying schedule and air velocity in softwood drying. In Proceeding of COST Action E15: Advances in Drying of Wood, Athens, Greece.

Shottafer, J.E.; Shuler, C.E. 1974. Estimating heat consumption in kiln drying lumber. Life Sciences and Agriculture Experiment Station, Technical Bulletin 73.

Siau, J.F. 1995. Influence of Moisture on Physical Properties. Virginia Polytechnic Institute and State University, New York, USA.

Simpson, W.T.; Tschernitz, J.L. 1980. Time, costs, and energy consumption for drying red oak lumber as affected by thickness and thickness variation. *Forest Products Journal* 30(1): 23–27.

Simpson, W.T. 1991. Dry Kiln Operator's Manual. U.S. Department of Agriculture Handbook AH-188, Madison, USA.

Skaar, C. 1972. Water in Wood. Syracuse University Press, Syracuse, USA.

Sparks, J.P.; Campbel, G.S.; Black, R.A. 2000. Liquid Water Content of Wood Tissue at Temperatures Below 0°C. *Canadian Journal of Forestry Research* 30: 624-630.

Taylor, F.W. 1979. Energy Consumption of Southern Pine Kilns. *Southern Lumberman* 215(2680):, 85-88.

Taylor, F.W. 1982. A comparison of energy requirements for kiln drying southern pine at different drying temperatures. *Wood and Fibre Sciences* 14 (4): 246-253.